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Scientific Paper No. 42

IMPACT OF OBSERVATIONS IN NWP MODELS: TECHNIQUES AND RESULTS OF RECENT STUDIES

by

M J Bader and R J Graham

5th November 1996

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1. INTRODUCTION

The observing process is the most expensive component of the forecasting system. Impact studies are a means of assessing the value of observing systems in terms of the benefit they deliver to model forecasts, and guiding efforts to ensure cost-effective deployment of observations.

More specifically, impact studies are usually carried out for one of the following reasons:

(a) To assess the impact of current operational observation systems on the accuracy of NWP forecasts,

(b) To ensure that new observations and new methods of using observations have a positive impact before including them in the operational assimilation (e.g. in recent times ERS-1 scatterometer winds and variational analysis of temperature soundings),

(c) To evaluate the likely benefit of proposed future observing instruments and to assess the impact of different instrument design options.

There are two main techniques for addressing the above tasks:

Observing System Experiments (OSEs) used for evaluating existing observations ((a) and (b) above).

Observing System Simulation Experiments (OSSEs) used to evaluate the likely impact of proposed future observing systems ((c) above).

The aim of this paper is to outline the techniques (Section 2) and then to bring together the results of recent studies (Section 3), many of which are documented in unpublished reports and conference proceedings.

In the review of the results, enough information has been provided for the reader to understand in general what has been done, the main results and where to find documentation on a piece of work. To avoid too much detail, we have not discussed the merits or otherwise of the assimilation scheme used. It should be remembered, however, that the OSEs measure the combined effectiveness of the observations and the data assimilation system. Hence their results must be interpreted with great care when seeking to draw conclusions about the observations alone.

2. IMPACT STUDY TECHNIQUES

2.1 Observing System Experiments (OSEs)

(a) Overview

Fig. 1 shows the basic form of an OSE. After selecting a period for study, two model assimilation runs are performed, one "with" and one "without" use of the data type we wish to evaluate. Each assimilation run is normally followed by a forecast. The benefit of the data is then assessed by evaluating the greater accuracy (if any) of the "with" forecast compared to that of the "without" forecast. A similar procedure may be used to assess the relative merits of different assimilation techniques; in this case the data presented to the assimilation are kept the same in both runs, and the method of assimilation for a given data type (or types) is varied.

As indicated on the diagram, verification may be performed either by comparing each forecast with observations or with model analyses. Each method has advantages and disadvantages.

> ***Verification against observations*** has the advantage that forecasts are compared with real data, but has the disadvantage that results will contain little contribution from the performance in data-sparse regions (e.g. over the oceans and therefore especially in the Southern hemisphere).
>
> ***Verification against analyses*** overcomes the problem of data scarcity. However, because of the role of the model background in the analysis, the "with" forecasts will tend to verify better than the "without" forecasts when the "with" analyses are used as truth; and vice versa when evaluation is against the "without" analyses. This difficulty is most acute in the early part of the forecast and in data-sparse regions.

There are two forms of assessment: statistical and case study. A combination of both approaches is often used.

(b) Assessment techniques

(i) Statistical assessment

Evaluation often takes the form of objective (statistical) assessments of impact on a number of forecasts over a specified period and geographical region (e.g., the tropics and extra-tropical regions of the N and S hemispheres). Evaluation based

on a single forecast per day for a period of 1-2 weeks is typical.

Experience at ECMWF has shown that the impact on NWP forecasts from changes to the assimilation are much less consistent, over a number of cases, than impacts stemming from changes to the model formulation. In order to obtain a statistically stable signal on the effect of a change to the assimilation scheme, it may be necessary to run more than 50 cases (Bernard Strauss, personal communication). This suggests that in data impact experiments, it is also necessary to run large numbers of cases to obtain a reliable signal.

Data impact is assessed by comparing forecast accuracy obtained with and without use of the observations under test. The assessment is expressed in terms of the improvement the data bring to statistical quantities such as mean error, root mean square error and anomaly correlation.

The main advantage with statistical assessment is that it gives a general result because it represents observation impacts on forecasts of a wide variety of flow regimes. Nevertheless, the following shortcomings should be borne in mind:

> Results will depend on model performance over the chosen period. For example, if forecasts without the data being tested are already good, there will be little scope for additional data to improve performance, and therefore little impact will be found. (Conversely a marked impact may be found with similar data over a period when forecasts without the new data are poor.)
>
> In the case of displacement errors, a model that produces a forecast with weak gradients (e.g., in MSLP) will tend to score higher than one which realistically maintains strong gradients because slight differences from the verifying analysis in the latter case will produce relatively larger errors.

OSEs of this type are sometimes performed in real time using the output from an operational model as the control run. A duplicate of the operational system is constructed, adapted to use the new data, and run "in parallel" with the operational system.

The main disadvantage of a real-time parallel experiment is that it has to be carried out during a pre-determined period. Features of the atmospheric circulation and model performance are therefore not known when the period is set. Results may be of limited value if a "quiescent" regime predominates over the region of interest or if the model's performance is different

from normal throughout the period of the experiment.

(ii) Case study assessment

Case studies are useful in the following ways:

to investigate the impact of observations for forecasting weather associated with individual weather systems (e.g., fronts, depressions),

to provide meteorological back-up to results of statistical assessments by relating them, for example, to features which are treated differently in the experimental and control runs.

Various ways are chosen to select cases. Examples are:

- looking for notable improvements in forecast skill between consecutive operational forecasts valid at the same time; these imply a significant impact from the additional information available for the later run (Graham et al 1996)
- choosing an interesting weather event
- choosing an exceptionally poor control forecast
- choosing a situation in which an impact is expected
- using results from a pre-planned field experiment.

In general the dependency of results on model performance, discussed above, also applies to case study assessments. However, it is possible to select only cases for which the model is known to be sensitive to initial data. The main disadvantage with case study work is the need to study many cases in order to gain generality in the results.

2.2 Observing System Simulation Experiments (OSSEs)

(a) Method

Clearly, the OSE approach cannot be used to evaluate a proposed observing system (from which there have not yet been any observations!) For this purpose the OSSE approach, illustrated in Fig. 2 is used. The method involves

- simulating the real atmosphere (with a model forecast - referred to as the "nature" run)

- simulating observations of the "nature" run; observations from both conventional and new systems must be simulated

- performing forecasts with and without the simulated observations from the new system.

The process is explained in more detail below.

(i) A long model forecast (typically 30 days) is performed. The output fields from this forecast (the "nature" run) become our surrogate for the real atmosphere. The nature run is used both as a starting point for simulating observations and as "truth" in verifying the forecast experiments. Note that in the surrogate atmosphere (unlike the real atmosphere) truth is known exactly at all model grid points.

(ii) Next, the distribution of the synthetic observations is determined. For simulation of the current observing system, the distribution is usually based on the global distribution of real observations at the corresponding time. For the future observing system it is necessary to construct the distribution from the proposed deployment. For satellite systems, for example, the distribution will depend on the envisaged orbit height and inclination and also on the instrument viewing characteristics. A number of different characteristics may be simulated and their impact compared.

(iii) "Perfect" observations are generated by interpolating the nature run fields to the observation location.

(iv) The "perfect" observations are then perturbed with errors characteristic of the observation type. This part of the simulation often requires much background study to determine the likely characteristic error of the proposed observing system being evaluated.

The procedure has been discussed in some detail by Stoffelen et al (1994b) (see also Becker and Roquet, 1995) who prepared an OSSE data set comprising 30 days of simulated measurements from a satellite Doppler wind lidar instrument, together with simulated measurements from other observing systems used in NWP.

Once the observations have been simulated, the procedure is similar to that for an OSE. At least two runs are performed:

- a run in which, for example, simulated data for all currently used observations are assimilated - the

control run;

- a run in which simulated data from the proposed observing system are also assimilated.

Comparison of the two runs with the 'truth' of the nature run gives a measure of the likely impact of the proposed observing system.

Although verification of the forecasts is usually performed against the nature run "truth", verification may also be performed against the synthetic observations. The latter method is more comparable to the verification process for OSEs and is preferable, therefore, for purposes of OSSE validation (see below) in which OSE and OSSE results are compared.

(b) Identical twin and fraternal twin OSSEs

Identical twin OSSEs

In early OSSE studies, the same model was used to assimilate the synthetic data (and to run forecasts) as was used to generate the "nature" run, or truth. In these so-called "identical twin" OSSEs the physical and dynamical processes in the assimilating model are identical with those in the surrogate atmosphere. Consequently, forecast errors arising from deficiencies in the model representation of the real atmosphere are not accounted for; only forecast errors due to errors in the initial conditions are represented. This limitation usually leads to over-optimistic results.

As Atlas et al (1985a) have pointed out, data "saturation" in the model will tend to occur at lower data volumes in an identical twin OSSE than for assimilation of the real observations. Data saturation (i.e. implying redundancy of some data) may lead to underestimation of the impact of observing systems with extensive coverage (e.g. satellite systems).

The lower threshold for saturation arises because the assimilating model can extract more information about the "nature run" than about the real atmosphere, from the same amount of simulated or real data. This is because observations from an "identical twin", unlike real observations, have characteristics (e.g. information on the scales of motion present) consistent with the model formulation. In contrast (though for the same reasons), identical twin experiments also tend to over-estimate the impact of sparse data (e.g. conventional observations).

Fraternal twin OSSEs

Forecast benefit derived from improvements in initial conditions

may, after a certain forecast range, become swamped by forecast errors arising from errors in model formulation. As mentioned above identical twin experiments take no account of errors in model formulation and therefore often lead to over-optimistic results. The fraternal twin procedure takes some account of the effect that errors in model formulation will have on the observation impact.

In fraternal twin OSSEs, the NWP model used to simulate the observations is different from the model used to perform the assimilation experiments (usually operational models from different NWP centres are used or the same model with coarser resolution). In this procedure the "true" atmosphere (the one used to simulate the data) has characteristics which are similar to but not identical with those of the assimilating model. The experimental procedure therefore parallels the circumstances faced in operational forecasting, in which NWP models behave in a similar but not identical way to the real atmosphere (at least up to about 5 days range, say). The fraternal twin method therefore brings more realism to the OSSE procedure by taking some account of the limiting factors that errors in model formulation impose on observation impact. The degree of realism is limited, however, since two NWP models (in an average or climatological sense) will often resemble each other more closely than either one resembles the real atmosphere.

(c) Validation/Calibration

The benefit of the simulated data in OSSEs is often found to be greater than that of the real data on operational forecasts. For example, pre-FGGE studies on the utility of satellite-derived temperature soundings gave over-optimistic results (Atlas, Kalnay and Halem, 1985b). Typical reasons for over-optimistic results are

1) The "nature" model and the model used to assimilate the simulated data are more similar than the real atmosphere and any model. This point has been discussed in Section (b).

2) The simulated observation error characteristics are too simple.

3) The simulated observation coverage is over-optimistic (e.g. the degree of cloud obscuration affecting measurements from satellite may be under-estimated).

4) The simplifying assumption, usually made in OSSEs, that the error characteristics of the observations are perfectly known. (Usually the observation error characteristics supplied to the assimilation procedure are the same as those used to simulate the observations. In contrast, we can only approximate the error

characteristics of real data).

To help correct for the tendency for over-optimism, OSSE results may be calibrated to corresponding OSE results. For example, the impact of simulated TOVS temperature soundings on OSSE forecasts can be compared with the impact of genuine TOVS on operational forecasts. Any over-optimism found in the OSSE results for TOVS may be used to "scale-down" the impact found from a new observation system being tested in the OSSE.

3. IMPACT STUDY RESULTS

3.1 Introduction to the tables

The information in the following tables summarises studies to evaluate the impact of different types of observation on NWP model forecasts. The aim is to provide the reader with a quick reference of what has been done and a brief guide to the impact found. An attempt has been made to include the most recent work. However, a few earlier studies have also been included because of their key contribution to the impact of a particular observation.

There has been a great deal of work worldwide to cover many different observation types. Some of the work has been published in the refereed literature; other work is found in conference proceedings and internal reports. Thus the authors do not claim that the review contains an up-to-date entry of all recent studies, especially outside the UK, and would welcome suggestions for further inclusion.

Included are studies on the impact from observational data which

(a) are currently included operationally in NWP,
(b) are currently available but not included operationally,
(c) could or will be available in the future.

Impact studies in Category (a) are carried out to determine which observations could be made more abundant to improve the forecasts or those that could be reduced in number or automated (e.g., to cut costs) without reducing forecast skill.

Observational data in Category (b) require impact studies before being accepted for operational use. Benefits of data in both categories can be assessed from both statistical and case study methods of OSEs described in Section 2.1.

Impact studies in Category (c) are carried out to assess the impact of a proposed observing system (often from satellite) and are in the form of OSSEs described in Section 2.2.

The advantages and disadvantages of each impact study technique have already been addressed in Section 2. The reader should be aware of these before referring to the tables.

Most studies listed in the tables report positive impact. However in a few, the impact of introducing some observations is negative. If assimilated correctly over a number of cases, no observation system should give a negative impact. A negative impact implies that the results are not statistically significant

or that there is a problem with the data assimilation scheme (e.g., inappropriate treatment of observation errors, poor quality control).

3.2 The tables

The information is divided into two main parts: impact of non-satellite and satellite observations.

The tables have three columns.

Column 1 - 'Reference' - contains the names of the author(s) and year when the reference was produced.

Column 2 - 'Method' - contains a brief description of what was done, the NWP model used and the forecast period.

Column 3 - 'Results' - is a summary of the impact, including dependence on region and forecast period. Orders of magnitude of the impact are included for some studies.

NON-SATELLITE OBSERVATIONS

SONDES

REFERENCE	METHOD	RESULTS
1. Heming, 1990	Study of explosive cyclogenesis case. Re-runs with and without upper air data from ships in the north Atlantic. Forecasts out to T+30 using UK limited-area model.	Upper air data from two ships at 35 and 37 deg west and ~6 deg latitude apart improved a depression's forecast position (by 200 km) and depth (by 8 hPa). The impact from each ship individually on the depth of the depression was 3 hPa.
2. Heming and Radford, 1993	Compared runs with and without TEMPSHIPS. Real-time 3 day parallel trial. UK global model forecasts out to 3 days; UK limited area model forecasts out to 36 hours. Impact variables: MSLP, 500 hPa height, 850 hPa RH, 250 hPa winds, rainfall.	Mixed or slightly negative impact overall with the TEMPSHIPS. Subjective verification revealed a small negative impact. Small positive impact in the limited area model for rainfall, especially over Europe. Positive impact on jet-level wind forecasts in the global model.
3. Pailleux, 1990	Parallel run for one week with and without TEMPSHIPS in the N Atlantic using ECMWF model. Also two other case studies. Forecasts out to 6 days. Impact variable: mean heights.	Modest positive impact over N hemisphere with TEMPSHIPS for 3 out of 10 cases; significant positive impact for 2; neutral impact for the rest. No significant impact beyond 3 days.
4. Travers and Heming, 1995	Series of 8 cases where sonde information from Campbell Island (500 km south of South Island) is removed and compared with results where the sonde data are included. Forecasts out to 60 hours using the UK Global model.	Impact of Campbell Island data was small in the New Zealand area. (The proximity of another upper air station 360 miles away may have reduced the impact.) There could be a situation (e.g. a southerly jet with a marked polar outbreak) when the Campbell Island upper air data could be vital.

5. Grant, 1995 (personal communication)	A study of three cases to assess the impact of radio-sonde observations from the UK Ocean Weather Ship. Forecasts out to 36 hours using the UK limited area model. Comparisons made with analyses of MSLP and rainfall at the verifying time.	Impacts from the Weather Ship's observations were negligible for these three cases. One case showed that a combination of the Weather Ship and an ASAP report produced a slight benefit.

BUOYS

REFERENCE	METHOD	RESULTS
1. Grant et al, 1996	Case study of 24 hour forecasts over the UK using UK limited area model with and without data from drifting buoys over the North Atlantic. Impact variables: MSLP, wet-bulb potential temperature at 850 hPa, 6-hour rainfall accumulations.	Significant improvement to the 24 hour forecast depth of an Atlantic depression and rainfall (position, amounts) associated with it.

WIND PROFILERS

REFERENCE	METHOD	RESULTS
1. Kuo and Guo, 1989	OSSEs to investigate impact on 80 km model of time-continuous observations from 77 wind profilers evenly distributed over USA with a station separation of 360 km. Focus placed on development of mesoscale circulations driven by large-scale forcing crucial for triggering convective systems and heavy precipitation. 24 hour forecasts using the Penn State University/NCAR mesoscale model. Results presented in form of vertically integrated rms error in wind speed, temperature and correlation coefficient of divergence.	Positive impact of assimilating profiler data in recovering mesoscale circulations and controlling error growth for large scale circulations. Particularly significant impact in the divergence field, crucial for an accurate precipitation forecast. A model experiment showed that assimilation of the wind field is more effective than assimilation of the temperature field. Best results when both temperature and wind fields were assimilated so profilers need to be complemented with independent temperature observations.

AIRCRAFT

REFERENCE	METHOD	RESULTS
1. Bell, Ingleby and Parrett, 1994	Assessed impact of US ACARS data in four cases. Compared forecasts against observations. Forecasts out to T+48 using UK global model. Impact variables: MSLP, temperatures, winds and humidity.	Improvement in rms scores. Best impact was about 3% at T+48 over Atlantic sector as information is advected downstream into verification area. Positive impact in structure, phase and strength of upper flow as features moved out into the Atlantic sector.

AIRCRAFT, WIND PROFILERS AND DROPSONDES

REFERENCE	METHOD	RESULTS
1. Smith and Benjamin, 1994	Series of parallel runs to compare impact of ACARS (wind and temperature data) and wind profiler data. Experimental runs excluding (a) all ACARS data, (b) all profiler data. 3, 6 and 12 hour forecasts using USA Mesoscale Analysis and Prediction System (MAPS).	ACARS data: Most impact on wind forecasts at jet levels only. Significant improvement in temperature forecasts. Profiler data: Improvement in wind forecasts at **all** levels plus a significant contribution at jet levels. Negligible impact on temperature forecasts. Strong impact from **both types** of data in 3h and 6h forecasts but not detectable at 12h; better forecast using **both data sources** together than just one.
2. Burpee et al, 1996	Computes differences in forecast tracks with and without dropwindsondes (wind, temperature, humidity) in environment and core of hurricanes. 17 cases from 1982 to 1993; 3 models.	Statistically significant reductions (16-30%) in 12-60 h mean forecast errors of tracks relative to control runs. Forecast improvements are up to 200 km for a single case.

SATELLITE OBSERVATIONS

TOVS DATA

REFERENCE	METHOD	RESULTS
1. Eyre et al, 1993	1-D VAR products (radiances instead of retrievals) were assimilated into the ECMWF NWP system. Background profiles were provided by the NWP model. 10-day forecasts were carried out in four different periods of about two weeks each. Main impact variables: 1000 and 500 hPa height.	Positive impact in N hemisphere from about Day 2. Up to about 1/2 day gain in forecast skill.
2. Gadd et al, 1995	In the experimental runs, the NESDIS 120 km temperature retrievals were replaced globally with a 1-D VAR method. Real time parallel trials using UK global forecasts up to T+72. Verification against analyses and observations. Impact variables: MSLP, height, temperature and wind.	Impact for height, temperature and wind: Against analyses: 90N-30N: Positive, all variables 90S-30S: Positive, all variables 30N-30S: Positive in temp; negative in height and wind. Against observations: 90N-30N: Positive, all variables 90S-30S: Positive in height and wind; negative in temp. 30N-30S: Positive in height and temp; negative in wind. Increase of forecast skill in extra-tropics of up to 11 hours.
3. Barwell and English, 1996	As in Gadd et al (1995), except for a tuning of the model and assessment of impact in forecasts up to T+120.	Positive impact over N hemisphere from Day 2. Gain of up to 6-8 hours in forecast skill after 3 days. Gain in skill of 10 hours for MSLP near UK. Positive impact in tropics for winds, heights, MSLP and surface temperature. Negative impact on tropical temperature profiles. Results over S hemisphere doubtful because of uncertainties with verification. More amplitude with stronger flow around larger scale ridges and troughs at 250 hPa.

4. McNally and Vesperini, 1995	Impact of assimilating humidity information from TOVS radiances in ECMWF humidity analysis was assessed. SSM/I total column water vapour (TCWV) was not assimilated but used as verification (both for 'control' and 'experiment'). Parallel assimilation experiments were carried out over four two-week periods. 3 and 5 day forecasts.	Analyses of mean fields of TCWV are improved. (A persistent area of large analysis error in TCWV over the tropical eastern Pacific has been removed.) Evidence of some improvement in predicting TCWV. In the S hemisphere, improvements are maintained longer into the forecast period. No clear impact in precipitation forecasts.
5. English et al, 1996	Assimilation as in Gadd et al (1995). Real-time 4-week parallel trial with and without humidity from TOVS in UK global model. Forecasts out to 5 days. Verification against analyses and observations.	Significant positive impact in forecasts of winds in tropics, upper winds everywhere, temperature and humidity in tropics. Benefits in relative humidity forecasts in all regions, mainly at mid-levels. Neutral impact for other parameters outside tropics.
6. Derber, 1996	Impact of cloud-cleared radiances in global 3D analysis (3DVAR) using the NCEP model. A 2-week trial for forecasts up to 5 days.	'RETRIEVALS-NOSAT' showed forecasts are degraded when weights from the retrievals are increased. 'RADIANCES-NOSAT' gave better forecasts. Results (using anomaly correlation) showed significant positive impact in the N hemisphere and even bigger positive impact over the S hemisphere.

CLOUD MOTION AND WATER VAPOUR WINDS

REFERENCE	METHOD	RESULTS
1. Radford, 1994	Added extra-tropical high-level winds from GOES/METEOSAT over land and extra-tropical high-level GMS winds over land and sea, plus removing extra-tropical low-level winds from GMS/GOES/ METEOSAT over land. Real-time parallel trial over 13 days using UK global model. Forecasts up to T+120. Impact variables: Heights, temperatures, winds, MSLP.	Greatest (mostly positive) impact between 30° and 90°S, especially from T+72 in height and temperature. Largest improvement in rms score was 2.7% in 850 hPa temperature at T+120. Marginal positive impact between 30° and 90°N. Positive impact over area covering a large part of North America, the North Atlantic and most of western Europe, especially at T+120. Changes in rms scores up to 1%. The results suggest that including high-level GMS data over the western Pacific is having a positive impact downstream in the medium range.
2. Kelly, 1993	An experiment with and without SATOBS using ECMWF forecast out to 10 days. Experiments lasted about 2 weeks each. Comparisons made with 500 hPa height obtained from conventional observations.	Over the N hemisphere, there is positive impact after 4 days when separately adding SATOBS or SATEMS; SATOBS give more impact than SATEMS; there is a gain in forecast skill of one day. Impact is less good when both types of data are included (indicating an assimilation problem). Another experiment showed neutral impact up to about day 4 then mixed impact after.
3. Grant and Bader, 1994	A case was studied in which cloud motion winds within a small depression over the North Atlantic were assimilated into the UK limited area model. Forecast out to T+24.	Improved forecast of amount and timing of rainfall over part of UK for this case.
4. Leighton, 1995	Impact of METEOSAT water vapour winds on 850, 500 and 250 hPa height, temperature, wind plus MSLP. Real time parallel trial over 27 days using the UK global model. Forecasts up to T+120.	Greatest positive impact in tropics. Greatest impact is at T+120. Over N hemisphere, slight positive impact overall, especially later in the forecast. Over S hemisphere, mixed impact. Generally positive for heights early in the forecast and negative for winds later. SATOBS improved the location of the sub-tropical jet.

5. Tomassini, 1996	Experiments, using the ECMWF analysis and forecast system over a two-week period, to assess impact of IR and VIS cloud motion winds (CMW) from METEOSAT. Impact variables: 850 hPa wind and height.	Positive impact globally, for forecasts up to 2 days, from low-level IR CMW, especially in tropics and S hemisphere. Here, RMS wind vector error in 24 h forecast decreases by about 20%. Small average impact of VIS CMW.
6. Leslie, Le Marshall and Spinoso, 1995	Impact, using the Bureau of Meteorology's global and regional models, on forecasting tropical cyclones out to 72 hours when varying spatial and temporal resolution of cloud drift winds.	The IR winds generated from half-hourly images reduced errors (by 10-15%) in forecasts of mean position of cyclone tracks over the Australian Coral Sea tropical cyclone basin. IR and VIS winds, used in a VAR assimilation experiment with a 2-D model, indicate potential for reducing forecast errors of mean track of tropical cyclones over NW Pacific and Australian regions.

SSM/I - TOTAL COLUMN WATER VAPOUR

REFERENCE	METHOD	RESULTS
1. Aune, 1994	Assimilation of total column water vapour from VAS on GOES-7 using the Regional Assimilation System of the USA Co-operative Institute for Meteorological Satellite Studies. 36-hour forecasts carried out during a 6 month period.	Modest impact to forecasts over the USA of precipitation (e.g., enhancing the band of precipitation along a cold front).
2. Ledvina and Pfaendtner, 1994	Assimilation of total precipitable water using the Goddard Earth Observing System (EOS) Data Assimilation System. 3-day global forecasts.	Reduction of model dry bias (total precipitable water) and increased globally averaged precipitation. Reduction of mean bias by 50% and rms error by nearly 30% after only 3 days of assimilation.
3. Wu and Derber, 1994	Runs of the USA NMC assimilation and forecast system with and without precipitable water. 5-day predictions in a 26-day period of assimilation. Impact variables: 1000 and 500 hPa heights.	Positive impact over S hemisphere: benefit increases with forecast time out to day 5. Improvements in forecast skill of a few hours at day 5.
4. Holt and Chang, 1994	Assimilation of precipitable water on forecasts of a rapidly deepening cyclone. The USA Naval Research Lab mesoscale model was used.	Small (beneficial) changes in position of the cyclone; reduction in central MSLP (up to 3 hPa) for forecasts of up to 24 hours.

SSM/I - PRECIPITATION RATES

REFERENCE	METHOD	RESULTS
1. Chang and Holt, 1994	Impact of assimilating SSM/I rainfall rates on forecasting of intense extratropical winter cyclones along east coast of USA. OSE and OSSE using the USA Naval Research Lab limited area model.	OSE: Forecasting of a rapidly moving intense cyclogenesis was improved. The error of the 24-h forecast of central pressure was reduced by 11 hPa. There were also improvements in the storm track forecast and structure. Improved precipitation forecast still noticeable 12 hours after assimilation period. OSSE: Improvement in MSLP forecast. Improvement insensitive to the error in rainfall magnitude estimates but sensitive to the location of the precipitation. More frequent observations had positive but gradually diminishing benefits.
2. Karyampudi et al, 1994	Assimilation of satellite-derived precipitation rates based on SSM/I and GOES IR rainfall data. 12-h simulations using the Penn State/NCAR mesoscale model (40 km grid).	Significant positive impact on central pressure and location of Hurricane Florence. Pressure is reduced by 10 hPa. Good agreement in rainfall pattern with the SSM/I data.
3. Peng and Chang, 1996	Assimilation of SSM/I retrieved rainfall rates using the USA Naval Research Lab limited area model.	Improvement on 48-h forecasts of intensity and track of Typhoon Flo. 48-h minimum MSLP reduced by 6-10 hPa. Distance error reduced from 239 to 81 nm.

SCATTEROMETER

REFERENCE	METHOD	RESULTS
1. Hoffman, 1993	Comparison of ECMWF model runs with and without scatterometer data for 11 days. An early version of scatterometer winds was used. Data were thinned to 100 km resolution.	Better low-level wind analysis (especially correcting overestimation of wind speed in warm air advection). But, overall, neutral impact of forecasts in S hemisphere beyond about 6 hours.
2. Stoffelen et al, 1994a (from Atlas et al 1994)	Impact of more recent (higher quality) ERS-1 winds on ECMWF Global Data Assimilation System.	Similar results to Hoffman (1993), using an early version of ERS-1 scatterometer winds. No significant improvement in forecast accuracy beyond 12 hours.
3. Gaffard and Roquet, 1995	Comparison between control and experimental forecasts (the latter including scatterometer winds) using the ECMWF model. 14 cases during a two-week period. Impact variable: 1000 hPa geopotential.	The impact of scatterometer winds is clearly positive on 12-hour forecasts for the S hemisphere only, but is mostly lost at 48 hours. For forecasts out to 10 days, the impact of the winds is slightly positive or neutral whatever the location. There is a maximum positive impact (up to ~1/2 day in forecast skill) over N America, probably because of a particular meteorological regime in the trial period.
4. Atlas, 1996	Experiments to evaluate the impact of ERS-1 scatterometer data on the Goddard EOS and NCEP model analyses and forecasts.	Positive impact for S hemisphere (12-h gain at Day 3); neutral impact in tropics and N hemisphere.
5. Bell, 1994	Compared model runs up to T+120 with and without scatterometer winds using the UK global model. A real-time parallel trial was carried out for 11 days. Note that the period includes cases where the original forecast was particularly bad.	Between 30° and 90°S, there is substantial positive impact. Average change in rms score for all variables for all forecasts: 3.7%; up to 10% reductions in rms errors for surface and low-level height at all forecast ranges. Improvements are greatest at shortest forecast ranges but much of the improvement is retained to medium range. North of 30°S: Neutral impact.
6. Bell et al, 1996	Experimental and control runs of the UK global model using the nudging analysis scheme. One forecast run to 5 days from each of 15 days.	Neutral impact in tropics and N hemisphere. Positive impact in S hemisphere out to medium range. About 1.8% improvement in rms MSLP errors (i.e., ~3 hours improvement in predictive range with equivalent skill).

LASER ATMOSPHERIC WIND SOUNDER (LAWS)

REFERENCE	METHOD	RESULTS
1. Atlas et al 1985a (from Baker et al 1995)	Initial OSSEs to assess potential impact of an idealized Doppler wind lidar on NWP at Goddard Space Flight Centre (GSFC). S1 skill scores averaged for eight forecast cases. Forecasts up to 5 days ahead.	For the S hemisphere, there was significant improvement in forecast accuracy resulting from the assimilation of simulated satellite wind data. The S1 skill score for 500 hPa height showed an improvement from 57 to 45 at T+5 when wind profiles were added; there were larger differences of S1 at shorter forecast ranges. Wind data are more effective than temperature data in controlling analysis error. In the N hemisphere, the influence of simulated wind profiles was smaller but occasionally showed a significant positive impact.
2. Atlas 1990 (from Baker et al, 1995)	OSSE to evaluate impact of lidar winds compared with very accurate temperature and moisture profiles. Conducted at GSFC.	All three types of data are important. However, the potential impact of lidar winds on atmospheric analyses and prediction was substantially larger than either of the other types of observations.
3. Rohaly and Krishnamurti, 1993	OSSEs simulating adding LAWS observations using the Florida State University primitive equation multilevel global model and the 4-D data assimilation system. Forecasts were carried out up to 5 days. Impact variables: 200, 850 hPa winds, 500 hPa height.	There was significant improvement in both analyses and forecasts for the S hemisphere (notably in mid-latitudes) and tropical oceans. Typical improvements in forecast skill are 1 - 2 days. In the tropics, without LAWS winds, the forecasts are not useful past day 1; with LAWS winds, the forecasts are useful to day 3.

RADIO OCCULTATION

REFERENCE	METHOD	RESULTS
1. Zou et al, 1995	OSSEs to assess impact of Global Positioning System (GPS) radio occultation data. GPS measurements were assimilated into a 60 km mesoscale model using 4-D VAR.	Rms errors of specific humidity suggest that GPS refractivity measurements should have positive impact on mesoscale data assimilation and NWP. For a global model, larger positive impact should be expected.

SATELLITE AND NON-SATELLITE OBSERVATIONS

ALL OBSERVATIONS USED OPERATIONALLY

REFERENCE	METHOD	RESULTS
1. Graham and Anderson, 1995 and also personal communication	20 case studies were used to rank benefits of all types of observations used operationally in the UK global model. Impact was assessed on 2-3 day forecasts. Impact variable: MSLP. (Satellite temperatures are retrieved temperature profiles (i.e. not 1D VAR or 3D VAR use of radiances.))	Out of 10 cases of marked beneficial data impact on forecasts for (i) North America and (ii) N Pacific and N Atlantic, a significant contribution to the beneficial impact could be attributed as follows. N American origin (10 cases): Aircraft winds in 6 cases Radiosonde winds in 6 cases Aircraft temps in 4 cases Radiosonde temps in 3 cases Cloud track winds in 3 cases Surface data in 3 cases Satellite temps in 2 cases R'sonde humidity in 1 case Scatterometer in 0 cases N Pacific/N Atlantic origin (10 cases): Aircraft winds in 9 cases Radiosonde winds in 7 cases* Surface data in 5 cases Radiosonde temps in 3 cases Satellite temps in 3 cases Cloud track winds in 2 cases Aircraft temps in 1 case Scatterometer on 0 cases * Many coastal stations contribute to these impacts.
2. Atlas, 1995	Six 5-day forecasts using the Goddard EOS 4-D Data Assimilation System. Comparisons between control assimilation using all conventional plus satellite data with experiments in which a particular observation type was omitted. Impact variable: MSLP. Verification against ECMWF analyses.	Observation — Impact SH* / NH* SATEM# + ~1d / + slight SATOB + 0.5d / - small PAOB + small / - negligible Aircraft negligible Ship+buoy + small / + small TEMP+PILOT + 2/3d / + 1.5d *Southern and northern hemisphere extra-tropics. +: Positive impact; - negative impact. Values in days. # from retrievals

CLOUD, HUMIDITY, PRECIPITATION RATE, SCREEN TEMPERATURE

REFERENCE	METHOD	RESULTS
1. Macpherson et al, 1995	Experiments using the UK mesoscale model. (a) Case showing impact of screen humidity data. (b) Average results from 5 cases showing impact of cloud data using surface observations and satellite images in the Moisture Observation Pre-processing System (MOPS). (c) Impact of MOPS data (cloud and precipitation rate) on precipitation forecasts. (d) Average results showing impact of screen temperature data for 9 cases up to T+18.	(a) Improvement of fog forecast over southern England (6 hours ahead). (b) Positive impact in forecasts of cloud cover up to T+18. Mean error and rms error reduced by typically half an okta. Benefit most persistent in anticyclonic cases (often with stratocumulus). (c) Most benefit in thundery situations with slack pressure gradients. One case showed benefit for ~9 hours into the forecast. (d) Reduction in rms error of 13% in screen temperature forecast at T+9. A small positive impact is still present at T+18.

BOGUS OBSERVATIONS

PAOBS

REFERENCE	METHOD	RESULTS
1. Seaman et al, 1993	Parallel trials with and without PAOBS (bogus values of MSLP) over two 4-week periods in different seasons. Forecasts up to 5 days using the Australian Bureau of Meteorology's global data assimilation and prediction system. Objective verification against analyses - using anomaly correlation coefficients skill scores for MSLP and 500 hPa height - and also against observations of height, thickness, wind, MSLP.	Inconclusive. Small positive impact on forecasts of broad-scale S hemisphere extra-tropical flow patterns up to 500 hPa.

4. DISCUSSION OF RESULTS

4.1 Impact of observations from satellites

(a) TOVS

The impact of temperature soundings retrieved from radiances measured by polar orbiting satellite has a long history; there have been many papers on the subject giving different results. It is therefore appropriate to give a brief review. Fuller details and references are given in, for example, Pailleux (1993) and Eyre et al (1993).

During and after FGGE in 1979, the impact on NWP of assimilating retrieved profiles from satellite observations was studied extensively using OSEs. A large positive impact was found over the Southern hemisphere where conventional data are very sparse. Over the Northern hemisphere, some studies showed a positive impact.

Other OSEs during the 1980s confirmed a positive impact in the Southern hemisphere. However as operational models improved, negative impact became as frequent as positive impact over the Northern hemisphere.

The basic problem with the satellite data is the rather poor vertical resolution of the satellite sounding radiometers resulting in information on some components of the profile, representing shallow vertical structures, being less accurate than can be supplied by the accuracy of the NWP model fields. In such cases, assimilation of these independently retrieved profiles will tend to degrade rather than improve the accuracy of the NWP model fields.

Recent work at ECMWF, NCEP and the UK Met. Office, cited in the tables, has shown that more careful attention to data processing and assimilation by direct use of TOVS radiances in a variational analysis (i.e., using observations in a form as close as possible to the quantities that are actually measured) has generally improved the impact.

With regard to the assimilation of humidity using TOVS radiances, older studies have shown that NWP models are rather insensitive to initial moisture conditions and quickly revert to a preferred climatology. However, more recent work by McNally and Vesperini using 1-D VAR to assimilate TOVS radiances in the tropics and Southern hemisphere (see tables) has shown considerable benefit of improved humidity analysis, especially for tropical NWP, but not necessarily positive impact in the forecast.

There is potential for greater impact on NWP models from

satellite soundings with data from instruments of higher resolution than those currently available e.g., improved infrared instruments such as IASI and HIRS in clear areas and improved microwave instruments such as AMSU in cloudy areas.

(b) Other satellite data

Experiments assimilating SSM/I data do show improvements in, for example, the analysis and forecasts of total column water vapour. Including precipitation rates from SSM/I data has improved forecasting the characteristics (e.g., central pressure and track) of depressions, including tropical storms and hurricanes. Experiments with SSM/I wind speeds (not tabulated) have shown significant improvements to ocean surface wind analyses in the tropics and Southern hemisphere (Atlas, 1995).

Upper winds from the motion of cloud and water vapour and near-surface winds from scatterometer data have demonstrated some benefit, especially over the Southern hemisphere and, for the cloud motion winds, over the tropics. OSSEs for the laser atmospheric wind sounder show promising results, with greatest benefit likely over the Southern hemisphere and tropics.

4.2 Impact of other observations

Significant benefit has been found from various types of upper air data: dropping sondes from aircraft into and around hurricanes, data from aircraft flying approximately at constant altitude and data from radiosondes. Winds from aircraft and radiosondes are found to be key elements of the observing network over the Northern hemisphere. In addition, positive impact for forecasts up to 24 hours has been found from wind profiler data over the USA, especially when combined with aircraft data.

Over the oceans, surface data contribute significant impacts relatively frequently. Thus a surface network with good coverage could partly compensate for the current lack of high resolution information in the middle and lower troposphere over the oceans. Surface data play a relatively less prominent role over land where radiosonde data and, in some areas, aircraft observations on climb and descent (Benjamin et al, 1991) provide high resolution data at mid- and low-levels. On the other hand, the beneficial impact of radiosonde and aircraft temperatures over land suggests that the high-resolution temperature information from IASI will be of considerable benefit to NWP analyses over the oceans, and will lessen the need for expanding the ocean surface network.

4.3 Observing 'sensitive' areas

Observations are likely to be most beneficial if they sample 'sensitive' areas of the atmosphere where errors in the operational analysis will have most influence on the subsequent forecast (see e.g., Rabier et al 1996). This has important consequences for observations in data-sparse areas:

Firstly, in a study to assess the cost-effectiveness of observations from a weather ship positioned west of the UK, fields of singular vectors showed that a sensitive area was close to the ship on only a few occasions during a period of several months (Graham and Klinker, 1995). This result provided evidence for deciding whether or not to continue observations from the ship.

A second application is when and where to make special observations. For example, sondes can be dropped from aircraft directed to sensitive areas where errors in the operational analysis will grow during the forecast. It is planned to test the feasibility of carrying out such observations in the FASTEX experiment (Snyder, 1996).

5. CONCLUSION

There is an increasing need to review networks of current observations, many of which have remained virtually unchanged over many years and are expensive to run. In addition, new observations (especially from ground-based remote sensing instruments and satellites) are continually coming on stream. It is important, therefore, to assess the benefit which observations deliver to NWP models in order to make the best use of the available resources.

In this paper, methods for carrying out impact studies have been reviewed and results from recent studies tabulated. It hoped that the contents will help readers working, for example, in NWP modelling and observation assessment to gain a good grounding of the subject and direct them to references where key impact studies have been documented.

ACRONYMS AND ABBREVIATIONS USED IN THE PAPER

ACARS	ARINC (Aeronautical Radio Incorporated) Communications Addressing and Reporting System
AMSU	Advanced Microwave Sounding Unit
ASAP	Automated Shipboard Aerological Programme
CMW	Cloud Motion Winds
ECMWF	European Centre for Medium-range Weather Forecasts
ERS-1	European Remote Sensing satellite - 1
FASTEX	Fronts and Atlantic Storm Track EXperiment
FGGE	First GARP (Global Atmospheric Research Programme) Global Experiment
GOES	Geostationary Operational Environmental Satellite
GMS	Geosynchronous Meteorological Satellite
GPS	Global Positioning System
HIRS	High resolution Infra-Red radiation Sounder
IASI	Improved Atmospheric Sounding in the IR
LAWS	Laser Atmospheric Wind Sounder
LIDAR	Doppler LIght Detection And Ranging
MAPS	Mesoscale Analysis and Prediction System (USA)
METEOSAT	European Geostationary METEOrological SATellite
MOPS	Moisture Observation Pre-processing System (UK)
MSLP	Mean Sea Level Pressure
NCAR	National Centre for Atmospheric Research (USA)
NCEP	National Centre for Environmental Prediction (formerly NMC, USA)
NESDIS	National Environmental Satellite and Data and Information Services (USA)
NMC	National Meteorological Centre (USA)
NWP	Numerical Weather Prediction
OSE	Observing System Experiment
OSSE	Observing System Simulation Experiment
PAOB	PAid OBservations i.e., code name for bogus MSLP values produced operationally in Australia
PILOT	Code for upper air report from a radiosonde (wind only)
RH	Relative Humidity
SATEM	SATellite TEMperatures
SATOB	Cloud Track Winds using consecutive images from geostationary satellite (SATellite OBServations)
SSM/I	Special Sensor Microwave Imager
TCWV	Total Column Water Vapour
TEMP	Code for upper air report from a radio-sonde (dry-bulb temperature, dewpoint, wind)
TEMPSHIP	Code for radiosonde observations from ships
TIROS	Television Infra-Red Observation Satellite

TOVS	TIROS Operational Vertical Sounder
VAR	VARiational data assimilation
VAS	VISSR Atmospheric Sounder
VISSR	Visible and Infra-red Spin Scan Radiometer

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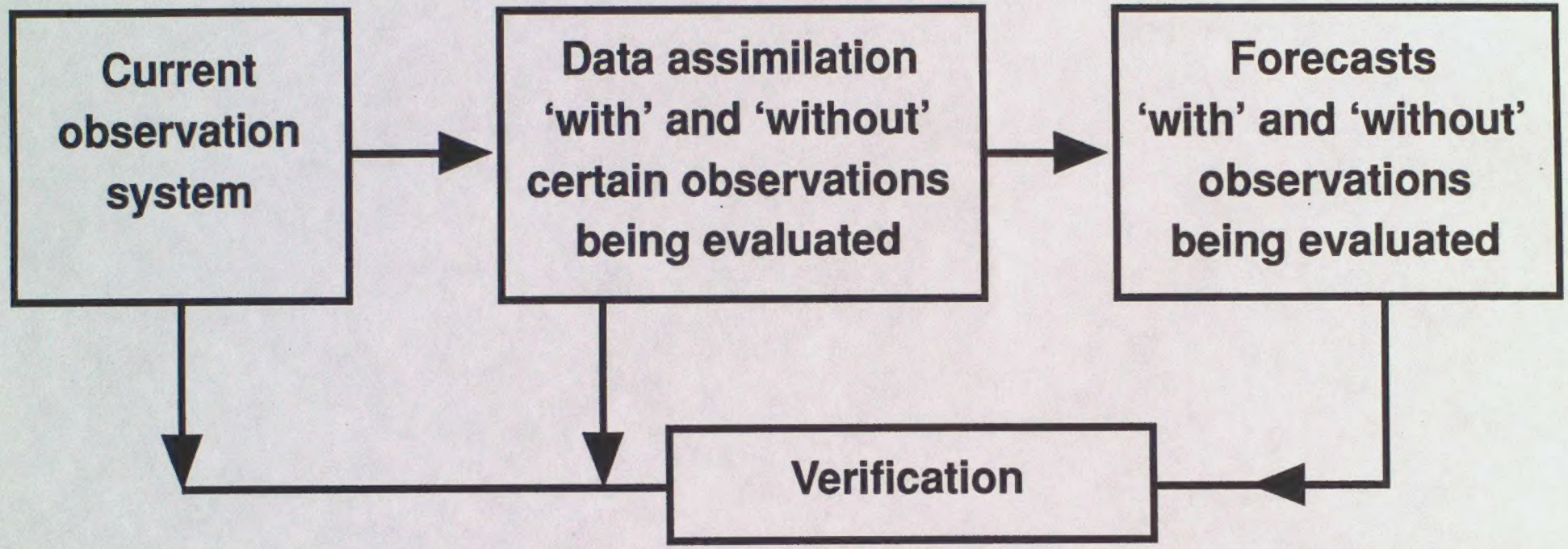
OBSERVATION SYSTEM EXPERIMENTS (OSEs)



Evaluation in form of:

- **Statistics for a number of forecasts**
- **Case studies of individual systems**

Fig. 1 Schematic of an Observing System Experiment (OSE).

OBSERVING SYSTEM SIMULATION EXPERIMENTS (OSSEs)

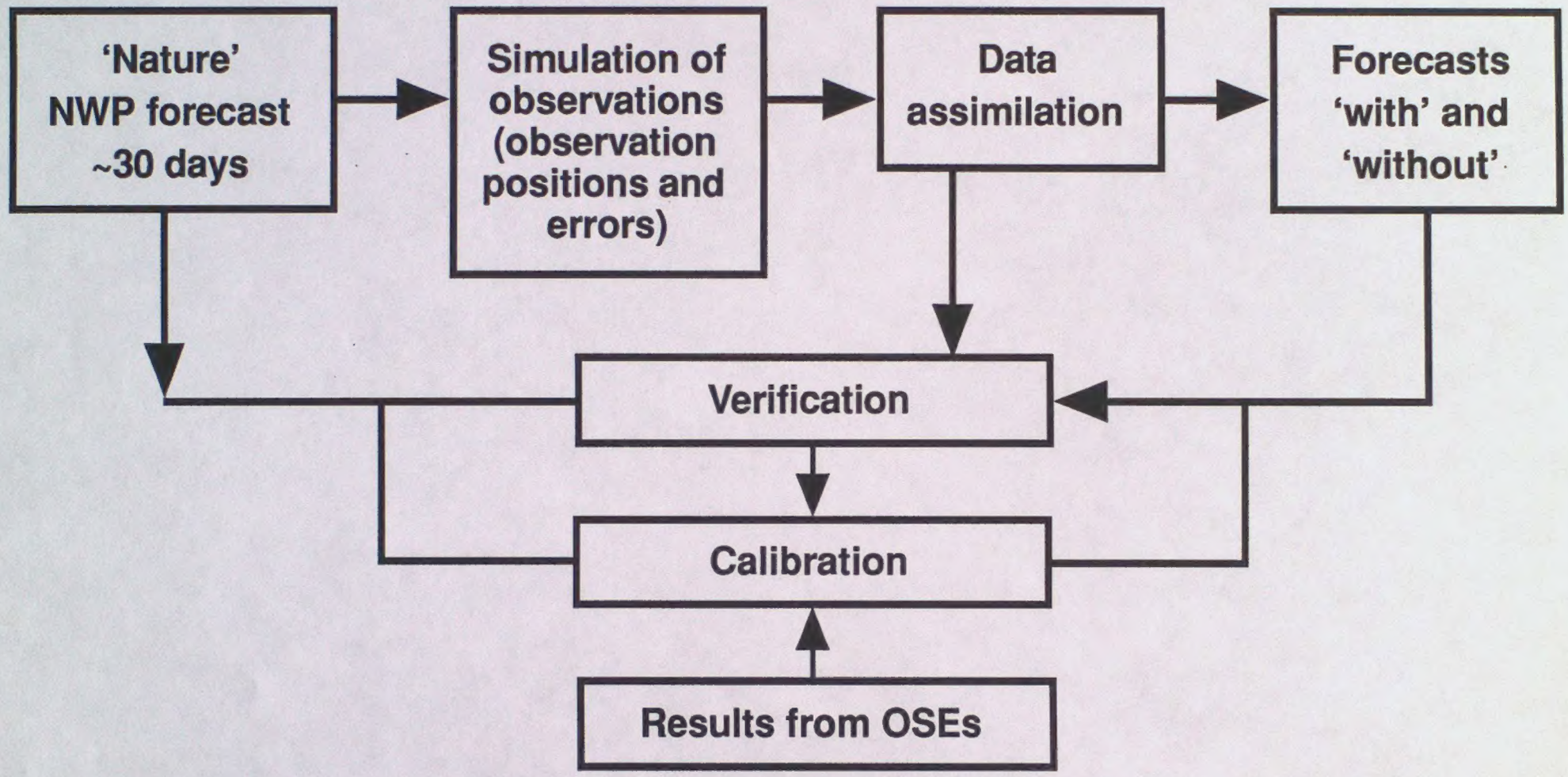


Fig. 2 Schematic of an Observing System Simulation Experiment (OSSE).